

## SolarPACES 2013

# Mechatronic platform with 12m<sup>2</sup> solar thermal concentrator for rural power generation in Africa

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## Abstract

Electrical power generation through Stirling type engines make use of concentrated solar radiation as the source of high-temperature heat. From a sustainable electrical power generation point of view, most rural African villages experience good concentrations of solar radiation, but rolling out reliable CSP solutions for tapping into this resource at rural African sites poses some system design challenges. This paper proposes a design for a 12m<sup>2</sup> parabolic dish frame which includes novel modifications over to the latest lightweight solar concentrators and aims to simplify assembly and installation of the solar concentrator platform at remote rural sites with unskilled support. The paper details the mechanical and mechatronic design challenges, solutions and selected results achieved in the quest to develop a stand-alone electrical power supply system for off-grid rural communities, research which ultimately aims to produce a locally manufactured knock-down do-it-yourself CSP power generation kit, suitable for distribution throughout Africa.

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## 1. Introduction

Collier *et al.* [1] predicted that the impact of climate change on Africa is likely to be severe because of adverse direct effects, high agricultural dependence, & limited capacity to adapt, while the role of governments needs to be to provide solar power technology, incentives, and economic environments to facilitate such changes. In terms of

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solar power generation technology, one of the first successful solar concentrator solar power generating devices was developed by McDonnell Douglas Aerospace in 1984 [2].

This 12kW<sub>e</sub> Stirling dish solar concentrator design included a balanced boom arm solar concentrator design, where the weight of the reflector dish on one end, and the receiver/generator on the other end, balances on a pivot point at the center of gravity of the balancing boom over the pedestal stand. The solar tracking design integrates a dual drive system to electronically control the movement of the curved solar reflector/concentrator in the altitude and the azimuth directions to ensure maximum heat to electrical power conversion through a Stirling engine.

Aiming to improve the conventional McDonnell Douglas design, the Infinia Corporation evaluated a number of solar concentrator designs to find a design for small scale solar power generation suitable for mass-manufacturing. Design generations include the Powerdish-I developed in 2006 to deliver 1kW<sub>e</sub> of electrical energy, Powerdish-II, a 3kW<sub>e</sub> system completed in 2007, and the popular Powerdish-III system, which saw the light in 2008 and has a power generation capability of 3kW<sub>e</sub> [3]. These designs focused on smaller supply systems, utilizing Stirling systems developed for spacecraft, for which the company was able to develop a smaller solar concentrator/reflector and less complicated solar tracking systems.

Under contract for the US Dept. of Energy, Murphey [4] designed a solar collector comprising a membrane for concentrating sunlight, a plurality of elongated structural members for suspending the membrane member thereon, and a plurality of cable control members for adjustably tensioning the membrane members. In this mechanical solar concentrator structure design, the optical focus produced by the membrane members could be controlled through the cable control members. This type of design, commonly referred to as stretched-membrane solar collectors, grew from idea to manufacture reflector modules for concentrating assemblies from thin, flexible, lightweight, reflector materials (i.e. thin metallic sheets of aluminum, steel or foils).

Shelef & Erez [5] later proposed a lightweight solar reflector concentrator design with a load bearing structure based on a tensile spoke-wheel, emulating a bicycle wheel structure. The hub & spoke structure is especially compatible with dish parabolic mirrors, but has utility as a carrier structure for any round functional surface, including flat or slightly-curved mirrors used in central tower solar systems, parabolic dishes for radio telescopes, as well as for non-concentrating thin film solar panels. In this concentrator design, the spokes pull the rim inwards, and the rim is compressed in the circumferential direction, while the ribs stiffen the spokes to resist wind and gravity loads to ensure structural stability to light-weight concentrator load bearing frame.

The Powerdish-IV solar concentrator design, released early in 2012 by the Infinia Corporation, also resembles the design structure of a spoke-wheel but include novel structural design concepts borrowed from the automotive industry [6]. The 3-3.5kW<sub>e</sub> system solar concentrator reflector frame includes a plurality of angularly placed elongated structural members which supports the parabolic concentrator mirror facets on a lightweight automotive steel chassis, structurally kept stable through cable trusses. The slewing actuator, comprising of two grease lubricated slew drives, allows tilt action for elevation movement and a pivoting azimuth movement, while and industrial standard PLC platform ensures electronically controlled solar tracking [6].

While Electrical power generation through CPV & Stirling type engines make use of concentrated solar radiation, and rural African villages experience good concentrations of solar radiation, rolling out reliable CSP solutions at rural African villages requires technology variations not always available in the western world [7].

The earlier Powerdish inventions [3] for example were claimed to be the world's first industrialized, mass-manufactured Stirling-based solar power system which enabled broad access to inexpensive solar power, these solutions are not suitable for rural Africa. In terms of remote solar power generation for rural African applications, though, a few features of these solar power generating systems are limiting its role in remote rural sites in Africa: the system requires a grid-connection for operation, the dish structure is complex and difficult to assemble at remote rural sites without skilled experts, and the large heavy mirror panels (especially of the Powerdish III) are expensive and poses damage risks with transport over large distances on rural dirt roads.

Lopez & Stone [8] investigated field problems on solar concentrator dish stations, and reported that oil leaks on the concentrator and actuator drives caused oil to spill onto the solar optic reflector mirrors, resulting in severe mirror soiling problems due to the oil attracting soil particles. Expensive manual scrubbing had to be employed to remove the oil from the dish mirrors. Such experience raise an alert against the use of oil lubricated tracking drives in solar concentrator design, suggesting that grease lubricated actuator drives for solar concentrators operating in extreme heat conditions would ensure fewer problems with field maintenance.

With the aim to produce a locally manufactured knock-down do-it-yourself CSP power generation kit, suitable for distribution throughout Africa, this paper describes certain aspects of the proposed mechatronic platform and parabolic solar concentrator system for stand-alone rural solar power generation. The design includes novel modifications over to the latest lightweight solar concentrators described before and aims to simplify assembly and installation, while reducing field maintenance in the solar concentrator platform for remote rural sites.

## 2. Mechatronic platform

This paper investigates key issues around the mechatronic design of a concentrated solar platform for electrical power generation through Stirling or CPV for rural Africa. The user specifications require a low maintenance, self-assembly kit, plug-and-play design for a self-tracking parabolic solar reflector system for Stirling/CPV solar power generation, which has the potential to provide  $12\text{kW}_t$  during Maximum Solar Altitude (MSA) at noon.

The designed mechatronic platform, providing for a type of mini solar power station suitable for CSP power generation in rural Africa, is depicted in a high-level block diagram illustrated in Fig. 1.

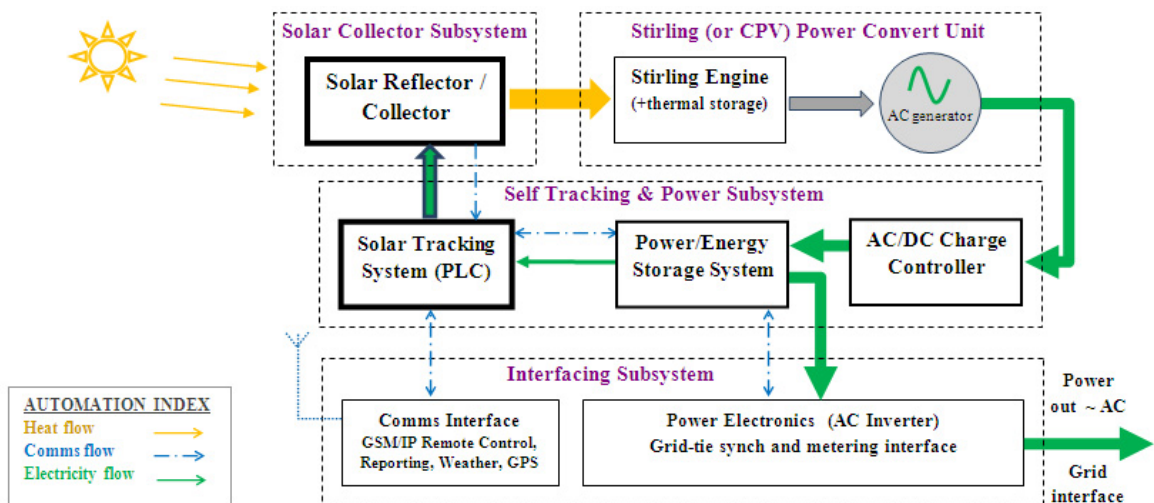


Fig. 1. High-level block diagram of the proposed mechatronic platform, emphasizing the Solar Collector and Self-Tracking Subsystems.

With reference to Fig. 1, the proposed platform consists of a Solar Collector Subsystem (a lightweight, easy-to-assemble solar collector for concentrating solar energy on the target), a Power Conversion Unit (developed in an associated study for converting solar thermal energy to electrical energy), a Solar Tracking & Power Subsystem (for dynamically steering the solar concentrator to pinpoint the concentrator on the sun, while managing onboard power), and an Interfacing Subsystem (for dispatching the generated electricity, and for interfacing with any remote control-, monitoring-, metering-, time synchronization-, or weather information- systems).

The full implementation of the mechatronic system and platform suitable for deployment at rural villages throughout Africa is described by Prinsloo [7]. This paper focus only on two elements in the design, namely design considerations, design choices and prototype implementation of the Solar Collector Subsystem. The Solar Tracking System and elements of these two subsystems is also described in this paper.

## 3. Solar collector subsystem

This section details the design of the solar energy collector system for Stirling or CPV solar electrical power generation. The user specifications require a design for a self-tracking parabolic solar reflector for Stirling/CPV with a potential to collect  $12\text{kW}_t$  during MSA (at noon). This relates to a solar reflector dish area of around  $12\text{m}^2$  [7].

### 3.1. Solar reflector design

Following the evaluation of a number of concentrator designs and testing a few scale models, this paper presents the chosen design- selected on the basis of weight, simplicity, structural stability and ease-of-assembly at remote rural sites [7]. The first prototype of the proposed concentrator design, shown in Fig. 2, includes a flat-lightweight load bearing structure, emulating a tensile spoke-wheel rim, fitted with a double parabolic reflector surface shaped out of composite material or individual mirror facets as optical reflecting surface.

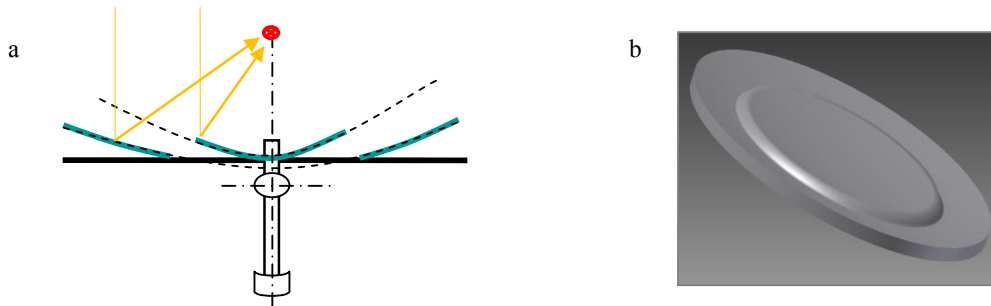


Fig. 2. Conceptual design of a dual-array parabolic solar thermal concentrator comprising easy-to-assemble structural basis and curved segments embedded onto a flat basis.

The base structure assembly has utility as a carrier structure for the concentrator (flat or slightly-curved) mirror facets. The mirror facets are fixed onto the load bearing structure in two circular arrays, forming an inner ring of a first parabolic dish with a ratio  $f/D=0.6$ , and outer ring of a second parabolic dish with a lower  $f/D$  ratio. The  $f/D$  ratio for the second parabolic element is chosen such that light reflection from both parabolic dish elements converges on the same optical focal point, while the base of the outer parabolic inner rim is fixed flush onto the load bearing structure. This design essentially describes a dual element parabolic Fresnel fitted onto an easy-to-assemble aluminum frame [7], while the design can be extended to include three or more parabolic ring elements as illustrated in Fig. 3.

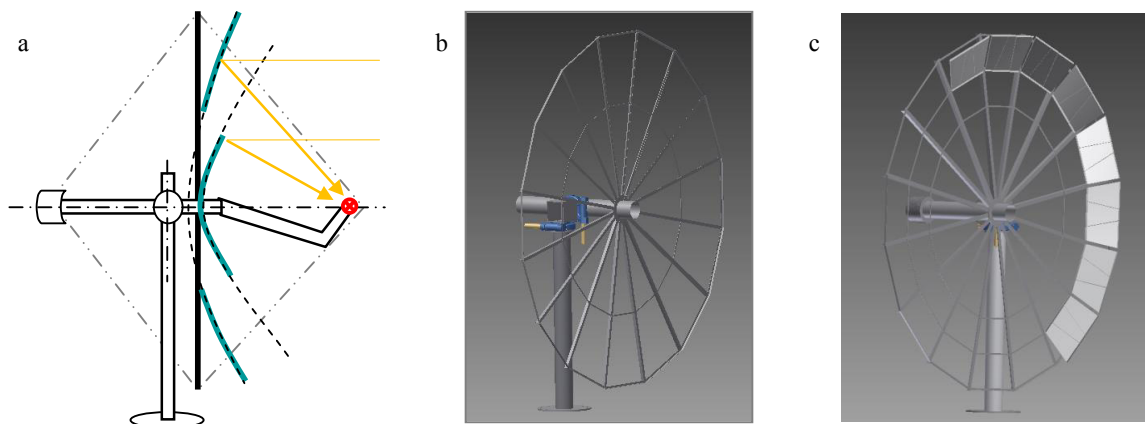


Fig. 3. CAD pictures of proposed concentrator, comprising flat structural frame fitted with parabolic reflector array rings, pivotally supported on pedestal through balancing-boom arm.

A cylindrical metal boom connects the hub of the concentrator frame structure with the counter-weight on one end of the boom and energy converting apparatus on the other end of the boom (at the optical focal point of the concentrator assembly). To ensure structural stability, the tensile spoke-wheel rim is compressed in the circumferential direction through aluminum rods/cable trusses between the concentrator rim and counterweight/focal point, forming a diamond like shape around the dish rim as shown with dotted lines in Fig. 3a.

The solar concentrator and mechatronic platform needed to be designed, implemented and tested at a typical site of installation in Africa. This mechatronic system also had to incorporate the design of a dual-axis altitude-azimuth actuator drive system, feedback sensing devices, and an electronic pointing and solar tracking control system to command the various modes of operation and states of control during pin-point accurate solar tracking and solar power generation.

### 3.2. Solar concentrator transmission system

The proposed solar concentrator and energy converting apparatus were designed to slew with the sun as as the concentrator is articulated about its rotational axis. A boom arm type slew configuration was chosen to realize solar tracking movement as this type of design ensures a counter-weight balanced device for moving, lifting and positioning of the solar concentrator. One benefit is that slew drives inherently present a self-locking solution to solar tracking and are presented by manufacturers as an optimum drive with low backlash [6] [9].

Slew is accomplished through a dual element actuator drive unit fixed onto a pedestal pole, and configured such to accommodate the concentrator movement through a main cylindrical boom element, diagrammatically displayed in Fig. 4. This mechanism allows unrestricted tilt action for boom/concentrator elevation while ensuring a swing-pivot azimuth movement in the horizontal direction.

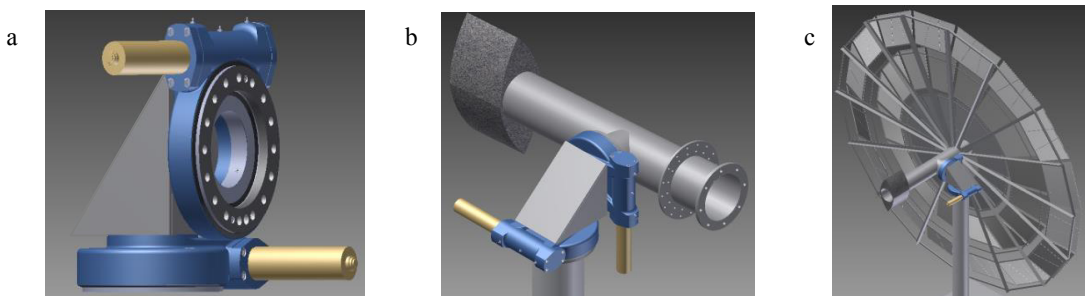


Fig. 4. CAD drawing & pictures of the supporting pedestal, dual-axis pivoting slewing actuator mechanism with DC motor drive assembly.

As shown in Fig. 4, two slew drive elements have been chosen as mechanism for pivotally mounting the solar concentrator frame to the main cylindrical boom. The first slew drive element ensures pivotal motion about an elevation pivotal axis, while a second slew drive element ensures pivotal motion about the azimuth axis. With constant aim azimuth movement combined with greater freedom of horizontal motion, this crane type slew design offers unique possibilities for solar concentrator movement and control.

The first slew drive element is mounted to the main boom and has a rotary output shaft aligned with the elevation pivotal axis, accordingly controlling the solar concentrator up-and-down movement. The second slew drive element A is mounted to the pedestal pole and has a rotary output shaft aligned with the azimuth pivotal action, accordingly controlling the solar concentrator left-right movement. Each slew drive element includes a DC electrical motor and a planetary gear unit to drive the main ring gear of the slew units.

A precise enclosed Slewing drive for Solar Tracker applications was sourced from H-Fang New Energy Equipment Company [9], selected on the basis of the proven track record and product axial and radial load & torque specifications required for the solar concentrator design [7]. These large-diameter, self-locking, anti-friction slewing drives comes equipped with a sealed raceway system, as a ready-to-install system with DC motor/planetary gear drive included. The housing is completely enclosed with sealed grease lubrication.

The proposed slew drive actuator solution uses grease as lubrication medium, instead of oil lubrication used in planetary and other gearboxes, leaving the proposed solar power generation system to be less prone to lubricant loss through shaft seals operating in hot operating environments. Grease lubricated slew drive actuators further does not require oil level sensors and minimizes the risk of excessive soiling from probable oil leaks, and poses less risk with drives not being able to run dry easily.

While a mechatronic platform for a rural CSP kit solution includes a simple modular solar concentrator design suitable for on-site assembling and simplicity in terms of installation features, rural CSP kit solution also requires a field proved, robust industrial standard automation platform.

#### **4. Self-tracking and power subsystem**

An automation platform is a mission critical component in the solar concentrator design, since any solar traction automation defect or operational problems would cause the solar concentrator system to lose its crucial connection to the solar resource. Any failure in the automation system would result in catastrophic operational failure from which the solar concentrator system would not be able to recover.

This section provides details of the automation platform, including the electronic control system, modes of operation, control logic and software integration.

##### *4.1. PLC automation platform*

Being in pursuit of an industrial grade automation platform, with low maintenance, self-assembly kit, plug-and-play features as prescribed in the user specification, the authors turned to the established automation industry in search of a suitable off-the-shelf plug-and-play type CSP automation solution which runs on an industrial standard PLC platform. An investigation into design options for the automation platform filtered down to the Rockwell Solar Tracking Automation solution running on an Allen Bradley PLC platform [10], and the Siemens automation software solution for Siemens Simatic PLC platforms [11].

The Siemens Simatic S7-1214C TIA industrial PLC platform [11] was chosen to implement the automation and solar tracking control for the new easy-to-assemble designed mechatronic solar concentrator platform for rural Africa. The Siemens solution was chosen for reasons of the proven track record of their PLC based solar tracking automation solution, remote control features, wireless remote access features, combined with Siemens' availability of the hardware components & spare parts, and backup service throughout Africa [7]. Siemens further provides off-the-shelf power modules for onboard power storage & dispatching of solar generated power, while Siemens supply off-the-shelf grid-interface modules for delivering solar generated power to any main electricity grid.

##### *4.2. PLC based solar tracking*

The astronomical algorithm calculations for the NREL solar position algorithm (SPA) have been written in PLC code by Siemens experts [12]. The code essentially implements the SPA on an S7-1200 controller as a function block (Fig. 5a) which is available as a run-time application for computing the solar vector for a given location and given time. The PLC code is used to compute the solar vectors (Fig. 5b) and Sun-Path Diagram data (Fig. 5c).



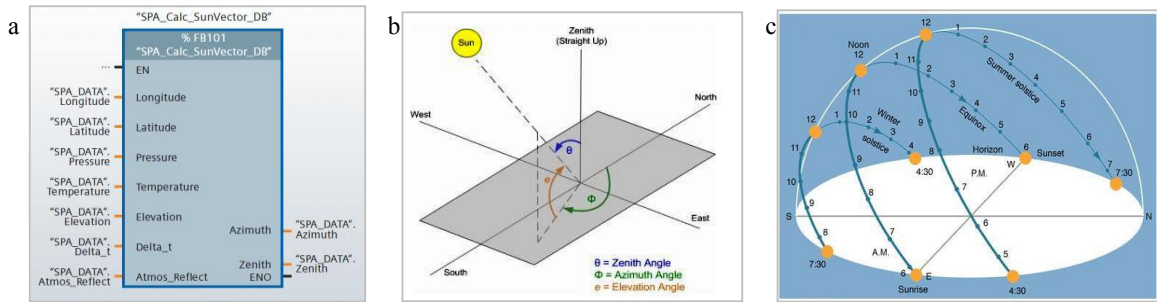


Fig. 5. Siemens S7-1200 (a) function block “Calc\_SolarVector”; (b) solar vector coordinate system; and (c) typical sun-path-diagram [12].

Thus, depending on the position of the earth, the position of the sun is calculated with the aid of this astronomical PLC algorithm, using details on the longitude and latitude location. The solar vector describes the required concentrator azimuth angle for the horizontal alignment and zenith/elevation for the vertical alignment. A sun-path-diagram depicts concentrator movements and stipulates the border regions and angular motion safety margins.

#### 4.3. PLC based solar tracking

Fig. 6 shows a block diagram to demonstrate the operational principles of the Siemens PLC solar tracking controller operating in open-loop control mode. The controller basically keeps record of the angular positions of the slew drives, determines the present solar position and compares the values to determine the motor control signals. In this configuration, the PLC performs solar tracking in open-loop controller mode, where the solar position is calculated from an astronomical algorithm (with the sun-sensor in the feedback loop in Fig. 6 omitted).

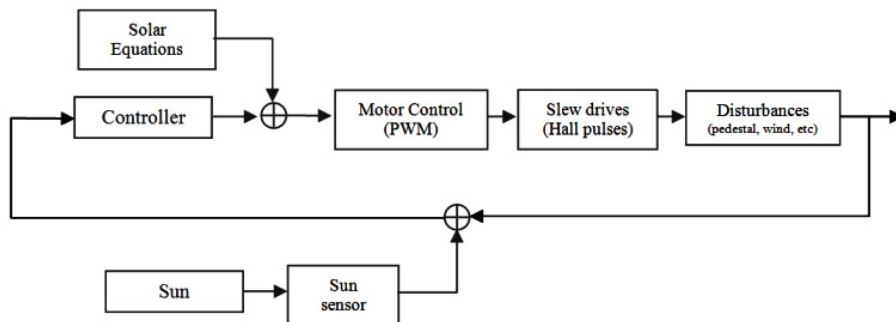
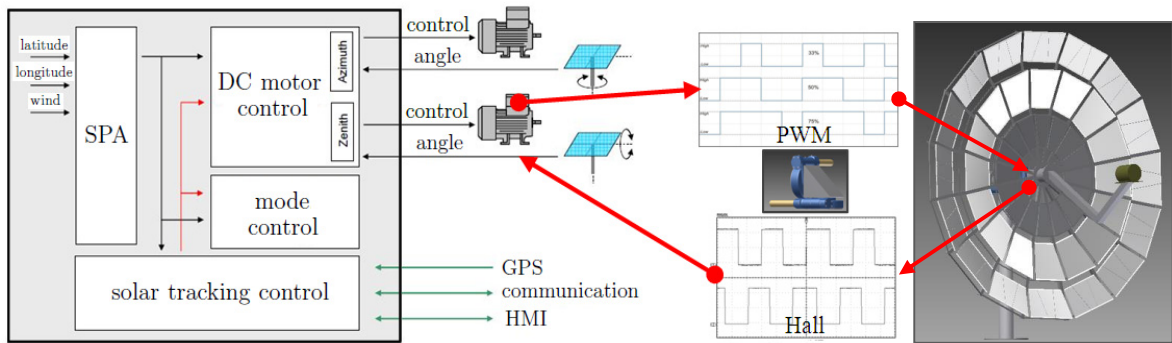


Fig. 6. Block diagram showing operational principles of the Siemens PLC Controller in open-loop/closed-loop control mode.

The feedback loop in Fig. 6 further demonstrates how the PLC can achieve more accurate solar tracking in an integrated open-loop control closed-loop controller mode. In this hybrid mode of control, the PLC receives input on the sun position from an astronomical algorithm as well as an optical means such as a sun sensor or imaging camera.

During configuration of the Siemens PLC solar tracking solution, the DC motor the speed specifications of the motor are stored in the motor setup. During solar tracking operation each DC motor movement instruction is fed from the PLC to the motor as a 24Volt PWM signal. In order to reduce the energy required for moving the DC motor on each axis, the DC motors are not moved continuously but intermittently. PWM signals are fed in time intervals associated with the solar contour movements so that the DC motors only draw current in intervals.

Fig. 7 shows the basic control configuration and demonstrates how the Siemens PLC software platform is associated with the slew drive tracking movement mechanism.



The current azimuth and elevation angle positions of the proposed solar concentrator, shown in Fig.7, can be detected using tilt sensors, angle sensors, shaft encoders, or Hall encoder. Each of the slew drives includes a brushless DC motor, each having its own Hall magnetic pulse encoder. The number of Hall pulses are recorded via the digital output port of the PLC controller and corresponds with the distance the drives has moved.

The digital output port of the S7-1200 PLC is also used for controlling the DC motors. The PLC employs Pulse Width Modulation (PWM) to control and vary the power and speed of the DC motors, which in-turn controls the azimuth and zenith/elevation angles of the solar concentrator through the slew drives. In the Siemens PLC software platform, control speed is standardized and computed around the specified set-point speed of the motor, while one of each of the DC motor power cables which carry PWM signals is wired with a shunting capacitor to the ground in order to reduce any radio frequency interference commonly caused by PWM control [11].

During the sun tracking control operation, each respective slew drive DC motor is powered independently through each of the two the PWM interfaces, while high-speed axis counters monitor the feedback of each of the two slew drive DC motor Hall encoders. The encoder pulse counts correspond to the desired travel path, and each motor is immediately stopped when the desired slew angle has been reached. Following each movement sequence, or during power down, the final axis counters are stored as part of the monitoring process, in order to continue with subsequent travel instructions from the former angular positions [11].

#### 4.4. Siemens PLC based solar tracking solution

Siemens offers an off-the-shelf solar tracking automation solution, designed to control double axis solar systems. Whilst facilitating solar tracking through a number of operation modes, the primary function of the solution is to ensure that the solar concentrator is pointed directly towards the sun for maximum exploitation of solar radiation.

Siemens' universal plug-and-play type solar tracking control solution, illustrated in Fig. 8, is suitable for dual axis solar concentrator automation applications on an industry standard PLC platform. The PLC platform and solution runs on the Siemens Simatic S7-1200 series controller, and ensures 64-bit arithmetic accuracy with precise azimuth and zenith/elevation solar positioning control through a very accurate astronomical algorithm. This algorithm is specified with leading edge accuracy of  $\pm 0.0003^\circ$  and can support solar tracking accuracies up to  $\pm 0.05^\circ$ . The Siemens PLC platform and software solution further provides for inputs to ensure error correction on mechanical tolerances and installation deficiencies. The central PC-based HMI can be connected through Ethernet/TCP connection and allow for configuration setup and calibration control inputs as well as for monitoring and control of the actual status of the solar tracker unit.



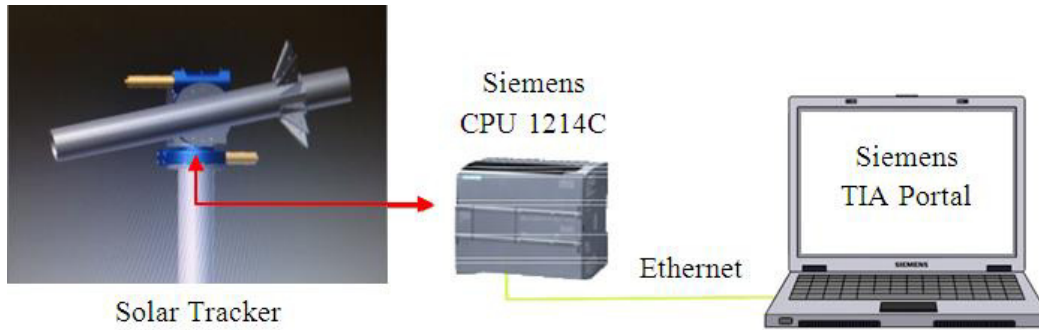


Fig. 8. Siemens S7-1200 PLC solar tracking controller linked to mechanical platform and HMI computer interface (Siemens [11]).

In order to start operations, the PLC software is downloaded to the PLC through a Memory Card or through a personal computer linked to the PLC through Ethernet/TCP connection. Following this, either an HMI or the Siemens Simatic software configuration tool Step 7 (Basic) or Siemens WinCC flexible runtime software can be used as user interfaces to configure the Siemens solar tracker to operate the PLC based solar tracking solution.

In case of failure, new controllers are available off the shelf at electrical distributors on every continent while replacement is easily accomplished by reloading the program from the memory card. The availability of remote monitoring and diagnostics features on the PLC interface further enhances troubleshooting and support maintenance.

One of the main tasks of the solar tracking controller is it to align the solar concentrator on a dual axis configuration, as closely to the solar vector as possible. The solar vector can be provided to the PLC through an astronomical algorithm or through inputs from external electronics.

## 5. Solar tracking accuracy datalogger

With the mechatronic aspects of the solar power reflector system designed and constructed, the system needed to be evaluated and its performance compared to similar systems under various operating conditions. In order to evaluate the solar tracking accuracy of the proposed mechatronic platform with solar concentrator design, a diagnostic instrument was built for measuring the tracker accuracy performance.

It was decided to develop a simple low custom made solar set-up diagnostic instrument which could be packaged with each solar concentrator system in order to assist the installers with automatic on-site calibration of the dual axis solar tracking systems, as well as for measuring and logging tracker accuracy performance. The proposed solar tracking datalogger is based on the MEMS ISS-CYPA Sun Sensor in a small housing, illustrated in Fig. 9.

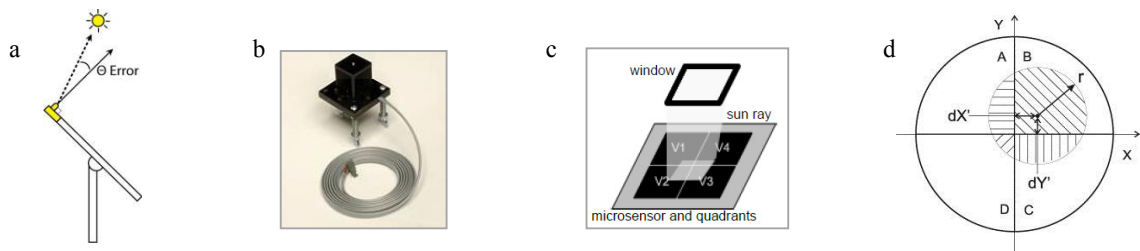


Fig. 9. Sun-sensor and operational principles behind of the solar tracking accuracy datalogger [13].

The MEMS Analog Sun Sensor (ISS-AX) has an easy interface with only 4 analog signals and it needs a simple calibration process after installation to set zero degrees position. This sensor allows for the measurement of the sun ray incident vector by providing its projection angles in two orthogonal reference axes, and it is made specifically for solar tracking applications [13]. This sensor is mounted onto the frame of the solar concentrator system to record

data through a PIC processor and a USB interface with a personal computer, to log data around the azimuth and zenith elevation "pointing error" using optical measures and some calibration calculations.

## 6. Experimental results

The performance of the mechatronic platform for the self-tracking solar concentrator positioning and control system was evaluated on the basis of the on-sun pointing azimuth and elevation off-target errors. With the dish reflector components still under construction at the time of preparation of the paper, the azimuth and elevation solar tracking errors were measured on a temporary cantilever boom. Fig.10 shows preliminary experimental results for the performance of the self-tracking positioning system located at GPS coordinates 33°S56' 18°E51' (Stellenbosch).

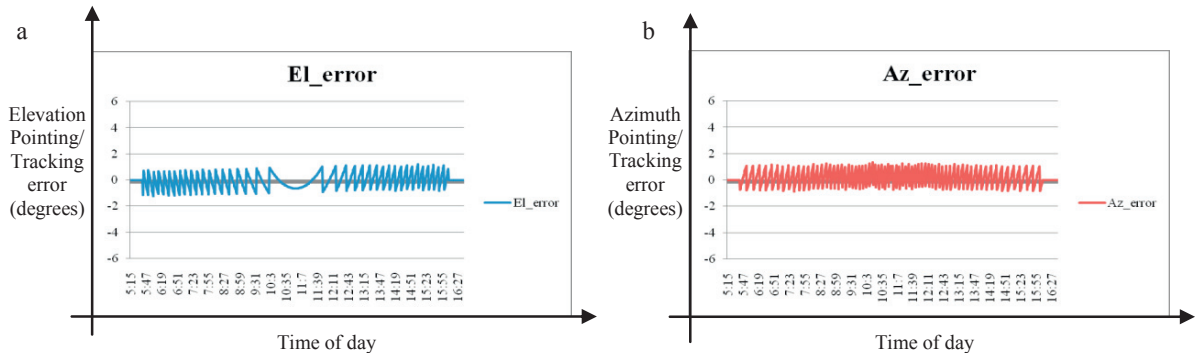


Fig. 10. (a) Elevation error; (b) Azimuth error pointing deviation (in degrees) for the solar concentrator mechatronic platform.

Fig.10 illustrates the logged solar pointing error measurements in terms of azimuth and elevation sun pointing errors over the course of one sample day (12-hour period). The data shows the elevation pointing error in Fig. 10a, and the azimuth pointing error in Fig. 10b. The oscillating effect of the PLC solar tracking control strategy can be observed in the time sequences of Fig. 10a and Fig. 10b. This oscillating nature in the tracking error is produced as a result of the PLC control philosophy and can be reduced by selecting a smaller tracking error window setting ( $\Delta$ ) in the PLC algorithm, keeping in mind that such reduced error would come at the expense of more frequent DC motor movements and potentially increased power consumption for the solar tracking operation.

In future studies, with the Stirling engine available, a balance will be found between the solar tracking error window setting ( $\Delta$ ) setting and the solar pointing error Stirling losses. Also in a follow on development, the solar tracking error datalogger will also be employed in a hybrid open-loop/closed loop PLC control mode. In this mode, the solar positioning algorithm data will be augmented with input from the sun sensor. The Siemens PLC provides for homing error settings to adjust azimuth or elevation PWM pulse sequences in relation to processed digital inputs from an optical device, such as the sun sensor.

## 7. Conclusion

This paper details the mechanical and mechatronic design challenges, solutions and selected results achieved in the quest to develop a stand-alone electrical power supply system for off-grid rural communities, research which ultimately aims to produce a locally manufactured knock-down do-it-yourself CSP power generation kit, suitable for distribution throughout Africa. The benefits of the solar concentrator platform include a plug-and-play type automation platform, low cost concentrator, slew drives use grease lubrication more suitable than gearboxes, light-weight dish as a result of cable trusses, weight balance over the pivot due to the counter weight, ease-of-access to the Stirling for maintenance, less wind resistance as a result of placement of mirror facets to ensure circular slots dividing the inner and outer rim mirrors, flatter dish structure with lower probability of dust fixation on the mirrors.

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